Columnar aerosol optical properties at AERONET sites in central eastern Asia and aerosol transport to the tropical mid-Pacific

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[1] The column-integrated optical properties of aerosol in the central eastern region of Asia and midtropical Pacific were investigated based on Sun/sky radiometer measurements made at Aerosol Robotic Network (AERONET) sites in these regions. Characterization of aerosol properties in the Asian region is important due to the rapid growth of both population and economic activity, with associated increases in fossil fuel combustion, and the possible regional and global climatic impacts of related aerosol emissions. Multiyear monitoring over the complete annual cycle at sites in China, Mongolia, South Korea, and Japan suggest spring and/or summer maximum in aerosol optical depth (τ_a) and a winter minimum; however, more monitoring is needed to establish accurate climatologies. The annual cycle of Angstrom wavelength exponent (α) showed a springtime minimum associated with dust storm activity; however, the monthly mean $\alpha_{440-870}$ was >0.8 even for the peak dust season at eastern Asian sites suggesting that fine mode pollution aerosol emitted from population centers in eastern Asia dominates the monthly aerosol optical influence even in spring as pollution aerosol mixes with coarse mode dust originating in western source regions. Aerosol optical depth peaks in spring in the tropical mid-Pacific Ocean associated with seasonal shifts in atmospheric transport from Asia, and ~35% of the springtime τ_{a500} enhancement occurs at altitudes above 3.4 km. For predominately fine mode aerosol pollution cases, the average midvisible (~550 nm) single scattering albedo (ω_0) at two continental urban sites in China averaged ~0.89, while it was significantly higher, ~0.93, at two relatively rural coastal sites in South Korea and Japan. Differences in fine mode absorption between these regions may result from a combination of factors including aerosol aging during transport, relative humidity differences, sea salt at coastal sites, and fuel type and combustion differences in the two regions. For cases where τ_a was predominately coarse mode dust aerosol in the spring of 2001, the absorption was greater in eastern Asia compared to the source regions, with ω_0 at Dunhuang, China (near to the major Taklamakan dust source), ~0.04 higher than at Beijing at all wavelengths, and Anmyon, South Korea, showing an intermediate level of absorption. Possible reasons for differences in dust absorption magnitude include interactions between dust and fine mode pollution aerosol and also variability of dust optical properties from different source regions in China and Mongolia.

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1. Introduction

[2] Atmospheric aerosol concentrations and their optical properties are one of the largest sources of uncertainty in current assessments and predictions of global climatic change [*Intergovernmental Panel on Climate Change* (*IPCC*), 2001; *Hansen et al.*, 2000]. Aerosol interactions result in both direct radiative forcing and indirect effects on clouds (droplet properties, cloud dynamics and lifetimes). Direct radiative forcings from aerosols are primarily a function of aerosol concentration in the total atmospheric column (aerosol optical depth), particle size distributions, and aerosol absorption properties. Satellite remote sensing techniques are beginning to provide more detailed information on the global distribution and dynamics of aerosol optical depth and also an estimate of the relative magnitude of fine mode versus coarse mode particles [*Kaufman et al.*, 2002; *King et al.*, 1999]. As most fine mode particles are anthropogenic in origin (primarily from fossil fuel combus-

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tion and agricultural biomass burning) and most coarse mode particles originate from natural sources (sea salt, airborne desert dust), this breakdown provides some measure of the anthropogenic contribution to the total aerosol burden. Exceptions to this simple categorization exist however as, for example, some natural aeolian desert dust is fine mode size and some fossil fuel combustion aerosols are coarse mode size, such as fly ash from coal combustion.

[3] However, satellite data does not provide complete characterization of aerosol optical properties, and information on aerosol absorption in particular is very difficult to derive from satellite remote sensing. Accurate knowledge of aerosol absorption magnitude is required for the assessment of both direct radiative forcing at the top of the atmosphere and at the Earth's surface [*Satheesh and Ramanathan*, 2000]. Additionally aerosol absorption information is critical in investigating the aerosol semidirect effect [*Hansen et al.*, 1997] whereby absorbing aerosols modify the surface and aerosol layer heating rates and therefore change the stability of the atmosphere and potentially alter the formation (or lifetime) of convective cumulus clouds [*Koren et al.*, 2004; *Ackerman et al.*, 2000]. On an even larger regional scale, simulations by *Menon et al.* [2002] suggest that absorbing aerosols in China may be responsible in part for the trend of increasing drought in northern China and increasing floods in southern China in recent decades. They suggest that the large-scale circulation and therefore hydrological cycle may be modified by the aerosol absorption that affects stability and vertical air motion. However, their study assumed highly absorbing aerosols in China, although very limited data on absorption are available in this region, and therefore the magnitude of the actual absorption is uncertain.

[4] Due to combined influences of arid dust production regions, large regional populations, and increasing fossil fuel usage, the East Asian region often experiences very high concentrations of tropospheric aerosols. This aerosol burden may increase in the future as both population and economic activity (and associated increases in fossil fuel usage) continue to grow. Estimates by *Wolf and Hidy* [1997] suggest that total particulate mass produced by China may increase by a factor of two to four (for a range of low to high fossil fuel energy consumption scenarios) over 1990 levels by the year 2040. In addition to the affects that these aerosols may have on regional climate forcings, possible reductions in crop productivity [*Chameides et al.*, 1999] and the health effects of aerosols on inhabitants of the region (and of megacities such as Beijing in particular) are also major issues of concern.

[5] The Asian Pacific Regional Aerosol Characterization Experiment (ACE-Asia) field campaign was conducted primarily in South Korea, Japan, China, and adjacent oceanic regions from late March through May 2001 to characterize the complex aerosol mixtures (pollution and dust) that occur there [*Huebert et al.*, 2003]. Spring is the peak dust production time of year, with the spring (March–May) of 2001 being a season of unusually heavy dust concentrations. The Aerosol Robotic Network (AERONET) site observations for this same region, presented in this investigation, cover the entire yearly cycle (including spring 2001 at some sites), therefore placing the aerosol characteristics and concentrations of the spring season in perspective within the annual cycle. One of the aerosol parameters that AERONET measurements and analysis provide is an estimate of column integrated aerosol absorption as parameterized by the spectral single scattering albedo (ω_0). *Nakajima et al.* [2003] emphasized that for the east China Sea region the springtime aerosol direct radiative forcing was highly dependent on the single scattering albedo, resulting in forcing differences of ~40% due to differing estimates of ω_0 obtained from measurements and models. In addition to data from AERONET sites in China, Mongolia, Korea, and Japan, we also analyze data from three sites in the Hawaiian Islands in this study, in order to investigate the long-range transport of aerosols in spring to the tropical mid-Pacific.

4. Summary and Conclusions

[38] Analysis of spectral aerosol optical depths and AERONET inversion retrievals of column integrated aerosol optical properties over the entire annual cycle were performed for several sites in central eastern Asia and the tropical mid-Pacific (Hawaiian Island chain).

[39] 1. Multiyear monitoring at four Asian sites (Shirahama, Japan; Anmyon Island, South Korea; Beijing, China; Dalanzadgad, Mongolia) show an extremely wide range in aerosol loading, from a yearly mean τ_{a500} of 0.77 at Beijing (city center) to 0.12 at a rural site in southern Mongolia (Dalanzadgad). The annual cycle of monthly mean τ_{a500} at most of these sites suggest a general spring and/or summer maximum and a minimum in winter, although continued monitoring is needed in order to more accurately characterize the annual cycle since only ~2 years of data has been collected at some of these sites.

[40] 2. The annual cycle of monthly mean Angstrom wavelength exponent ($\alpha_{440-870}$) at these same four Asian sites show minimum values in spring (March–May) during this season of maximum dust storm activity. However, the monthly mean minimums of $\alpha_{440-870}$ for all months at all of these sites exceed ~0.80 even in spring, therefore suggesting that while desert dust contributions to total aerosol optical depth are significant, fine mode pollution aerosol contributes more to the optical depth during the entire year at these locations. However, for a site west of Beijing in a more arid region and downwind of major dust sources (Yulin, China), the Angstrom exponent ranged between 0.3 and 0.4 in March and April of 2002, thus dust aerosol strongly dominated the optical depth in spring 2002 in this location.

[41] 3. Multiyear monitoring of aerosol optical depth in the tropical mid-Pacific shows a strong maximum in March–May due to transport of aerosol from Asia eastward in that season. Measurements made at Mauna Loa Observatory at 3.4 km altitude and at Lanai near sea level (~200 km apart but >8000 km from the Asian sources) suggest that ~35% of the springtime enhancement in τ_{a500} is from aerosol above 3.4 km altitude. In 2001, the springtime peak τ_{a500} in April at near sea level in Midway was ~0.21, nearly twice as high as at Lanai (~0.11) since Midway is ~7.5° farther north in latitude and therefore in a zone of stronger eastward transport and also ~2000 km closer to Asia than Lanai. In the nonspring months of July–December 2001 the τ_{a500} at Midway and Lanai were nearly equal ($\Delta\tau_{a500} < 0.01$).